Time-dependent thermal X-ray afterglows from GRBs

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Abstract

Time-dependent thermal X-ray spectra are calculated from physically plausible conditions around GRB. It is shown that account for time-dependent ionization processes strongly affects the observed spectra of hot rarefied plasma. These calculations may provide an alternative explanation to the observed X-ray lines of early GRBs afterglows (such as GRB 011211). Our technique will allow one to obtain independent constraints on the GRB collimation angle and on the clumpiness of circumstellar matter.

1 Introduction

X-ray afterglows of GRBs were first discovered by Beppo-Sax satellite (Costa et al. 1997) and their spectral observations are now used for plasma diagnostic of the plasma surrounding GRB cites (Lazzati et al. 1999; Piro et al. 2000). The most exciting observations are now available from *Chandra* and *XMM-Newton* X-ray satellites. Recently, Reeves et al. (2002a,b) reported on *XMM-Newton* observations of the early afterglow spectrum of GRB 011211. These observations, taken $\sim$ 11 hours after the GRB, revealed the presence of emission lines which were fading over a time scale shorter than 10^4 s. These lines were interpreted as blue-shifted (with a velocity of $\sim$ 0.1 c in the GRB comoving frame) K_α emission from ions of α-elements (Mg XI, Si XIV, S XVI, Ar XVIII, Ca XX) arising in a dense ($n_e \sim 10^{15}\,\mathrm{cm}^{-3}$), optically-thin thermal plasma shell heated by the GRB. The model requires a factor of 10 overabundance of α-metals in the plasma. No iron lines were seen, however.

If this interpretation is correct (see the criticism in Borozdin and Trudolyubov 2002; Rutledge and Sako 2002), this could strongly point to a supernova (SN) explosion preceding the GRB (the supranova model; Vietri and Stella 1998). The apparent absence of iron lines is explained by Reeves et al. by possible peculiarities of the SN ejecta. It is worth noting the claims (Watson et al. 2002) that three of four GRB X-ray afterglows observed by *XMM-Newton* are best-fitted by thermal plasma model.

The emission line origin in GRB 011211 was critically considered in several papers (Kumar and Narayan 2002, Lazzati 2002). Our study (which we have reported at this meeting before the latter paper was posted in astro-ph e-print archive) re-examines the X-ray emission line origin in thermal plasma model. In contrast to other studies, we investigate time-dependent ionization effects in thermal plasma. We show inconsistency of the model proposed by Reeves et al. (2002a) for GRB 011211 and propose another interpretation of what was observed. Specifically, in our model the observed non-stationarity of emission lines is directly related to time-dependent character of collisional ionization in thermal optically thin plasma with clumps of lower density ($n_e \sim 10^{11} - 10^{12}\,\mathrm{cm}^3$). Such a plasma can be found around the GRB or just spuriously occur near our line of sight.

However, in our model it is difficult to explain the observed blueshift of lines by a supernova preceding the GRB for only a few days. In the thermal model, no individual lines can be reproduced from fresh hydrogen-helium SN ejecta even enriched in metals (there is no space near the GRB source to get the needed emission measure). Purely metal ejecta are much more efficient X-ray emitters, they can be placed closer to the GRB, but then, as our computations show, one would rather observe the metal photorecombination edges, not lines, from a recent (a few days old) SN ejecta. The ten-times metal overabundance is also unnatural for fresh ejecta, because modern paradigm of massive star SN explosions assumes purely metal ejecta (for SNe Ic). If real, the blueshifted lines should be emitted at much larger distance from the GRB engine, so they could originate in the material expelled by a supernova much earlier, maybe some years before the GRB, and this material can be mixed with the H-rich circumstellar matter.

2 Time-dependent emission lines from thermal plasma

The thermal emission model assumes collisional ionization of atoms and is applied to rarefied plasmas heated by an external source (the solar corona provides an example). Photons originating in atomic transitions, in radiative recombination, etc. leave the plasma freely. The plasma cooling time depends on density and chemical composition; for example, for a fully ionized plasma composed of ions with the charge Z,

$$t_c \approx 2 \times 10^{15}\,[s] \left(\frac{T}{10^8}\right)^{1/2} n_i^{-1} Z^{-2} \approx 2 \times 10^{15}\,[s] \left(\frac{T}{10^8}\right)^{1/2} n_e^{-1} Z^{-1} \tag{1}$$

The numerical factor in this formula is valid with the 20%-accuracy for a purely hydrogen plasma. Clearly, this formula gives an *upper limit* for the cooling time in real plasmas.

For densities $n_e \sim 10^{15}\,\mathrm{cm}^{-3}$, advocated by Reeves et al., the plasma cools faster than in 1 second and a stationary thermal model is appropriate. At lower densities, for example, $n_e \sim 10^{11} - 10^{12}\,\mathrm{cm}^{-3}$, the cooling time becomes much longer than the heating time $t_h \sim 90$ s (the GRB 011211 duration in its rest frame) and time-dependent effects must be taken into account. The relevant parameter here is nt. For large nt, plasma relaxes to a stationary state.

In the case of GRB X-ray afterglows, the non-stationarity has two faces. On one hand, the real X-ray spectrum could change over the integration time in the detector (~ 5000 s for GRB 012111) due to temperature decrease even if the plasma density is high and the parameter nt formally allows for stationary ionization. On the other hand, when nt is small, relaxation effects could cause ions to appear which were absent in the stationary case. We stress here that there is strong dependence of plasma cooling time on the metallicity. The real cooling time depends on ionization states and abundances of different ions so time-dependent effects play significant role in low-density plasma.

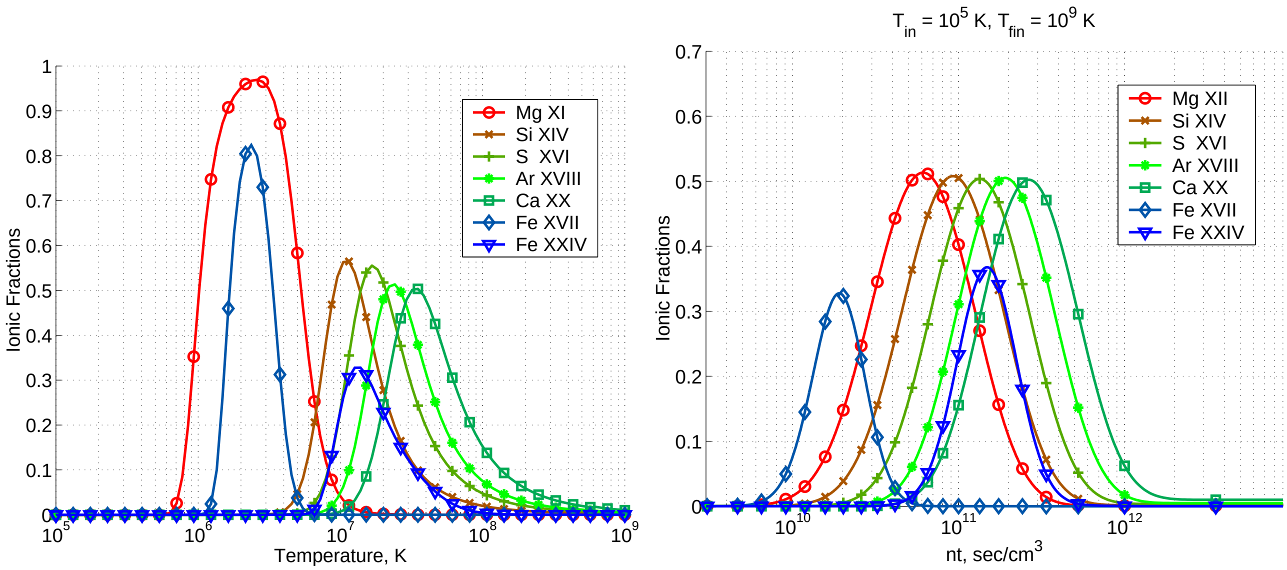

Figure 1: Relative number densities of ions as a function of temperature for stationary case (left panel) and as a function of time for time-dependent model (right panel).

This latter face of non-stationarity is illustrated in Fig.1 which shows relative number densities of some ions as a function of temperature (for stationary case) and as a function of the parameter nt for time-dependent ionization. In the latter case, an initially cold plasma (10^5 K) with density $n = 10^{12}$ cm^{-3} is instantly heated up to a temperature of 10^9 K. This figure indicates that during thermal relaxation of plasma, ionization state *at a given time* can be close to some stationary ionization state at different fixed temperature.

3 X-ray afterglow of GRB 011211

X-ray afterglow of GRB 011211 was observed by *XMM-Newton* ~ 11 h after the GRB (Reeves et al. 2002a,b). The emission lines faded away over a time interval of 10^4 s. The volume emission measure as inferred by Reeves et al. from the average X-ray luminosity 7×10^{45} erg/s for plasma with normal cosmic abundance is EM $= n_e^2 V = 10^{69}\,\mathrm{cm}^{-3}$. As we discussed above, such an estimate is only the *upper limit*, since real plasma can have higher volume emissivity and smaller cooling time.

3.1 Thermal model by Reeves et al.

According to the model by Reeves et al. (2002a), the observed X-ray spectrum originates in a dense $n_e = 10^{15}\,\mathrm{cm}^{-3}$ shell of radius $R = 10^{15}$ cm and thickness $h = 10^9$ cm expanding with a velocity of 0.1 c from GRB, as the mean redshift of the identified lines ($z = 1.88$) implies (the GRB host galaxy redshift is $z = 2.14$). As such a dense plasma cools down in 1 s, the observed fading time of X-ray lines ($t_1 = 10^4$ s) is explained by the light retardation from different parts of instantly illuminated shell (this geometrical effect was invoked by Lazzati et al. 1999 to explain the X-ray afterglow evolution of other GRBs).

This model have obvious caveats which makes its applying to GRB 011211 questionable.

- **Short plasma cooling time:**
  If cooling time is as short as 1 s, an overwhelming part of the observed X-ray emission must be generated during illumination of the plasma by gamma-ray radiation from the GRB (t_h = 90 s in the GRB rest frame). The time evolution is then entirely due to the retardation, i.e. to the geometrical effect. This implies that the observed X-ray photons were actually generated *simultaneously* with the powerful illumination by hard photons from the GRB. Then, in order to explain the corresponding X-ray spectrum the photoionization (nebular) approximation but not the thermal (coronal) one should be used. However, the photoionization model is claimed to be inadequate (Reeves et al. 2002a). In order to try to explain these observations within the frame of a thermal plasma model, we must assume much longer cooling time $t_c > t_h$, hence lower plasma densities.

- **Large emission measure:**
  The EM in this model is determined from the mean X-ray continuum luminosity and with the assumed density $n_e = 10^{15}$ cm^{-3} relates to the layer volume $V = R^2h = (10^{15})^2 \times 10^9 = 10^{39}$ cm^3 which we observe in 1 s. As the X-ray luminosity is registered over 10^4 s, there must be 10^4 such volumes! This contradicts the assumption that one and the same shell of radius $R = 10^{15}$ cm and thickness $h = 10^9$ cm is emmitting. So in order to save the model, on has to assume the existence of clumps with size $l = 10^{12}\,\mathrm{cm} \gg h$, which are optically thick at such densities.

- **Apparent absence of iron lines:**
  The explanation was that iron ^{56}Fe does not have enough time to be produced from the radioactive ^{56}Ni expelled by SN. Under special assumptions about SN II mechanism one can obtain the deficit of iron isotopes (Rausher et al. 2001). However, if the plasma shell in this model is indeed expelled by SN, such an SN is hardly to be typical – in particular, it can be asymmetrical. So the initial amounts of iron, nickel, and cobalt can be comparable. Asymmetric explosions of SN that may be connected to GRBs give different results (Pruet et al. 2002). Some model calculations of hypernovae by Umeda et al. (2002) yield up to 40% of prompt iron isotopes. So the iron yields in SN ejecta are strongly model-dependent, and the apparent absence of iron in the X-ray spectrum can not provide a reliable argument in favor of a supernova associated with the GRB.

- **High density and high velocity of the shell:**
  Physical characteristics of the SN ejecta as a dense rapidly expanding shell also meet difficulties. Similar dense shells are produced in radiation hydrodynamics calculations of SN (Falk and Arnett 1977; Chevalier and Klein 1979; Blinnikov and Bartunov 1993), but their properties are quite different. The total energy of the shell in the model by Reeves et al. approaches the typical SN explosion energies, while the dense shells arising in hydro calculations either have smaller masses or lower velocities, of order of several 1000 km/s (Chugai et al. 2002) and carry only a small fraction of the SN explosion energy.

3.2 Thermal model with time-dependent ionization

In our model, the observed X-ray fading time t_1 is identified with thermal relaxation time of a plasma heated up by GRB.

3.2.1 Emitting region geometry

Let the GRB occurs inside (or nearby) a star forming region of complex clumpy structure. This assumption is quite natural and have solid observational support (van Paradijs et al. 2000). In order for plasma cooling time (1) to be 10^4 s, the gas density must be $n_e \sim 10^{11} - 10^{12}\,\mathrm{cm}^{-3}$. To obtain the observed EM ($n_e^2 V \lesssim 10^{69}\,\mathrm{cm}^{-3}$, the volume of the emitting region must be $V \lesssim 10^{47} - 10^{45}\,\mathrm{cm}^3$. At the same time, it must be optically thin for X- and gamma-ray photons, $nl\sigma_T \sim 1$, where $\sigma_T \sim 10^{-24}\,\mathrm{cm}^2$ is Thompson electron cross-section. It is hard to meet both conditions in a homogeneous medium, but a more realistic rarefied plasma with clumpy structures can do the job.

Indeed, let us consider $\sim 10^6$ gas clouds with density $\sim 10^{12}\,\mathrm{cm}^{-3}$ each and a size $\sim 10^{13}\,\mathrm{cm}$. The total volume of the dense component in such clouds amounts to the required value 10^{45} cm^3 and gives the necessary EM $= 10^{69}\,\mathrm{cm}^{-3}$ (we recall that these are upper limits; for example, using realistic plasma cooling function with normal cosmic abundances yields EM $\sim 4 \times 10^{68}\,\mathrm{cm}^{-3}$ and solar plasma without H and He yields EM $\sim 10^{65}\,\mathrm{cm}^{-3}$, see also Fig.2). The total mass of the emitting clumps is less than $\sim 0.3 M_\odot$. Clumps of such densities and size are indeed observed as maser condensations in stellar winds from young stars and late-type stars. The total volume occupied by this inhomogeneous medium is determined by energy balance and the width of a gamma-ray beam.

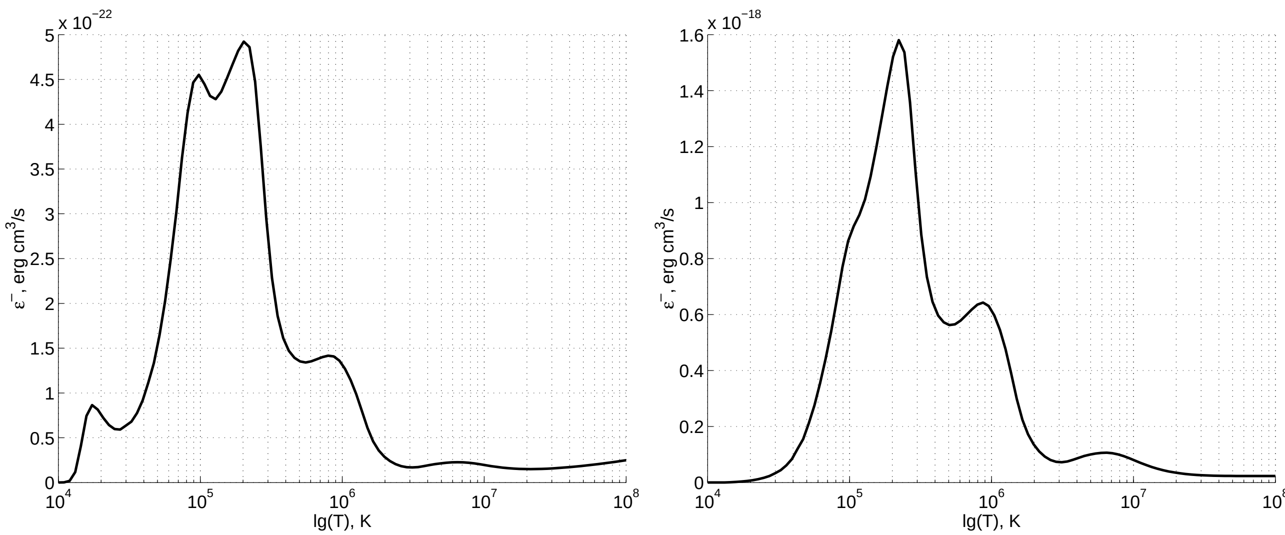

Figure 2: Plasma cooling function ε^- (erg cm^3 s^{-1}). **Left panel**: solar composition, then the emission measure for $T = 10^8$ K is EM $= n^2 V = L_X/\varepsilon^- \simeq 3.7 \times 10^{68}\,\mathrm{cm}^3$; **Right panel**: metal-rich medium (without H and He), EM $= n^2 V = L_X/\varepsilon^- \simeq 1.4 \times 10^{65}\,\mathrm{cm}^3$

Heating matter up to 10^8 K would require energy deposit $\epsilon_0 = 10\,\mathrm{keV}$ per nucleon, i.e. the energy $E_\mathrm{h} = 10^{12}\,\mathrm{cm}^{-3} \times 10^{45}\,\mathrm{cm}^3 \times 10$ keV $= 10^{48}$ erg is necessary. The total isotropic energy of GRB 011211 is $E_\gamma = 5\times10^{52}$ ergs. The effective cross-section of gamma-ray energy deposition per nucleon with good accuracy is $\sigma_\gamma \simeq 0.1\sigma_T$ (Ambwani and Sutherland 1988). Considering the fluence from the source at a distance d to be $F = E_\gamma/4\pi d^2$, the heating energy per nucleon is $\epsilon_0 = \sigma_\gamma F$, so

$$d = \sqrt{\frac{\sigma_\gamma E_\gamma}{4\pi\epsilon_0}} \simeq 2\times10^{17}\ \text{cm}$$

I.e. the GRB energy is sufficient to heat up surrounding matter up to distances $d \simeq 0.1$ pc. Note that F plays more important role than E_γ; it is measured by our detectors (at larger distances of course), and no assumptions on gamma-ray emission beaming should be made to estimate d.

The gamma-ray beam opening angle θ determines the total volume of the illuminated matter. The simple geometry leads to the estimate

$$d(1-\cos\theta) = ct_1/(1+z) \simeq 10^{14} \quad \text{cm}$$

Assuming not very large angle (which appears natural in view of the large value of isotropic E_γ) we have $d(1-cos\theta) \simeq d\theta^2/2$, i.e. the illuminating gamma-ray beam size is $R \simeq \theta d = (2d\,ct_1/(1+z))^{1/2} = (2\times10^{14}\,\text{cm}\times d)^{1/2}$. For example, $R \simeq 10^{16}$ cm for $d = 2\times10^{17}$ cm and $\theta \simeq R/d = 0.05$, i.e. 3° (the total beam angle is twice as large, $2\theta = 6°$).

The total volume of the medium illuminated by GRB is quite large, $V \sim R^2 d = 3\times10^{49}$ cm^{-3}. We stress here that though gamma-ray photons from GRB fly this distance d in several months, they reach the detector simultaneously with X-ray photons they created passing the clouds, so X-ray emission comes not from a dense shell 10^{14} cm in thickness but from an extended clumpy region with the size of order of d. The filling factor of this medium can be 10^{-4} or larger if the condensations are located in a relatively thin layer and not across the entire distance d. This simple estimate shows that the physically acceptable structure of a clumpy ISM can actually be the source of the observed X-ray emission.

The necessity of clumpy structure of emitting plasma was also obtained by Lazzati (2002) from independent analysis of stationary thermal X-ray afterglows from GRBs. We stress again here that in contrast to Lazzati, we do not require the shell around the GRB, for us it suffices that the medium with the required physical parameters lies in the cone of the gamma-ray beam. This plasma can be not genetically connected with GRB. In our model, orphan X-ray afterglows can well show transient emission features like those observed in the case of GRB 011211.

3.2.2 Spectral modelling

To model X-ray spectra from thermal plasma, including the case of GRB 011211, we utilize numerical code originally worked out by P. Lundqvist for calculations of collisional ionization of a stationary plasma, which has been elaborated by S.I. Blinnikov and E.I. Sorokina into a time-dependent variant. To calculate time-dependent spectra, the temperature dependence on time $T(t)$ is needed. The plasma cooling function ε^- (erg cm^3 s^{-1}) is almost independent of temperature for 2×10^6K – 10^8K (see Fig.2). Then the temperature change with time can be found from the differential equation

$$\frac{dT}{dt} = -\frac{\varepsilon^-(T_0)n_e^2}{C_V\rho}$$

where $C_V = (3/2)\mathcal{R}(1/A+X_e)$ is heat capacity per unit mass at fixed volume, $\mathcal{R}$ is the universal gas constant, A is the mean mass of ions in atomic units, X_e is the number of free electrons per nucleon, $T_0 = 10^8$K is the initial temperature. Then in the above temperature range the temperature decreases linearly with time

$$T(t) = T_0 - \varepsilon^-(T_0)n_e^2 t/(C_V\rho) \tag{2}$$

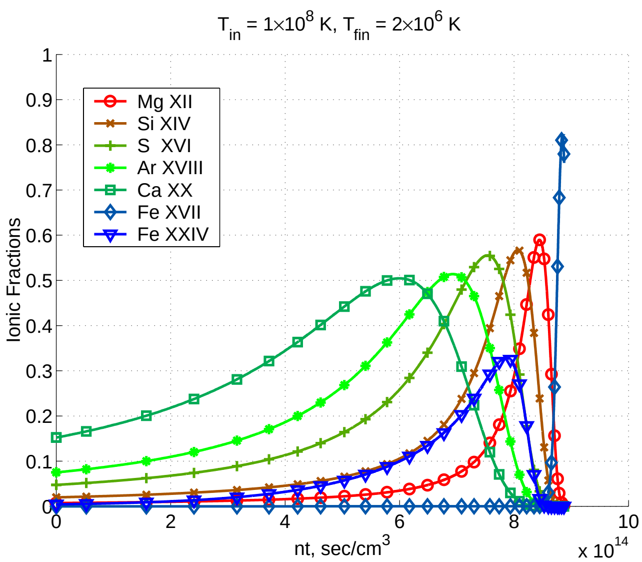

Figure 3: Relative number densities of ions as a function of the parameter nt for linear plasma cooling law (2). **Left panel:** solar composition; **right panel:** metal-rich plasma (without H and He)

The time evolution of ion number densities (Fig.3) is calculated numerically and determines the appearance of the corresponding emission X-ray lines (Fig.4). These figures show strong time evolution of thermal spectra from optically thin cooling plasma initially heated by GRB up to 10-keV temperatures. For normal cosmic abundances, emission lines from moderately ionized iron atoms immediately appear. As plasma cools down, lines of H-like and He-like iron emerge (Fig.4). If metal enriched (and, correspondingly, with deficit of H and He) SN ejecta is observed, emission lines from metals become more prominent against the continuum. At late cooling stages, photorecombination edges of metals prevail (Fig.4).

4 Discussion

Analysis of our calculations of emission spectra from thermal optically thin plasma suggests that interpretation of early X-ray GRB afterglows in term of thermal model requires (1) a moderate density of the emitting plasma ($n_e \sim 10^{11} - 10^{12}\,\mathrm{cm}^{-3}$), and (2) a clumpy structure of the circumstellar (interstellar) medium. In our model, X-ray line emission forms not necessarily in matter genetically related to gamma-ray burst source, it is sufficient for it to lie within the gamma-ray illumination beam at distances $\lesssim 0.1$ pc from the GRB site. Specifically, for the

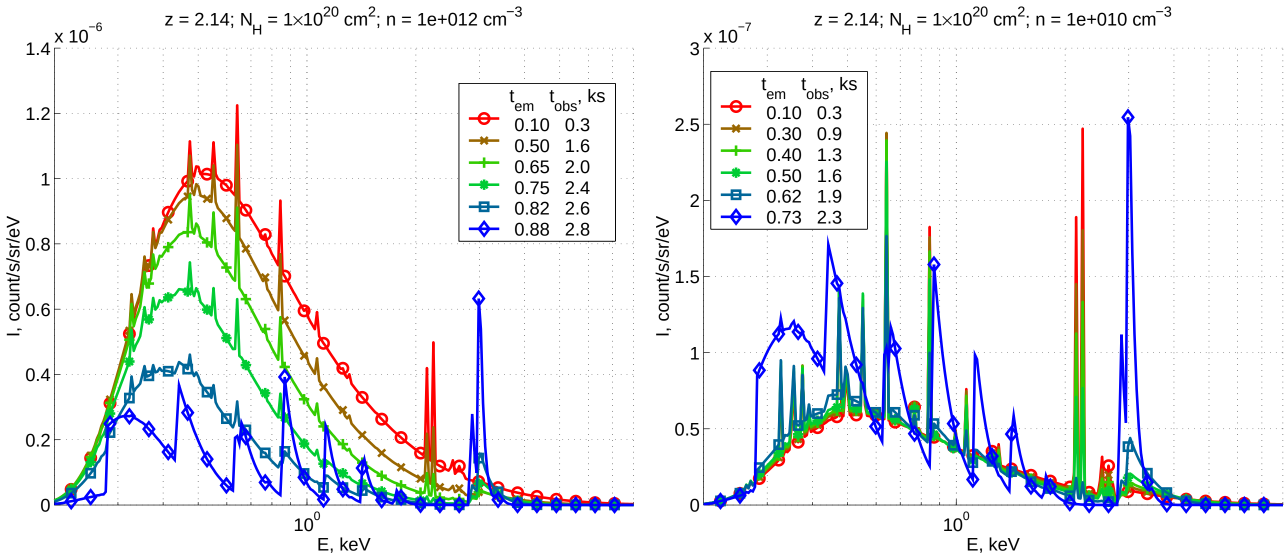

Figure 4: Time evolution of X-ray spectrum (in the observer frame at the GRB redshift $z = 2.14$) for different time moments. **Left panel:** solar composition; **right panel:** metal-rich plasma (without H and He)

observed parameters of GRB 011211, $L_X(0.6-30)\,\mathrm{keV} \approx 7\times 10^{45}$ erg/s (in the source rest-frame), a total of $\sim 0.3M_\odot$ of matter comprised in clouds ~ 1 AU across inside a volume of $\sim 10^{49}\,\mathrm{cm}^3$ illuminated by gamma-ray beam with the full width $2\theta \sim 6^\circ$ would suffice. Note that such narrow angles are generally obtained in the standard model interpretation of time decay of GRB afterglows (Frail et al. 2001). The parameters of individual clouds are also astrophysically feasible and correspond to dense maser condensations in star-forming regions.

The proposed model interprets the observed temporal evolution of X-ray spectrum in terms of thermal relaxation time of ions and plasma cooling, and does not appeal to purely geometrical arguments. However, the comparison of the calculated spectra with those observed by Reeves et al. does require enhanced α-metal abundances. The apparent absence of iron lines either require its underabundance, which is less probable according to current SN nucleosynthesis, or can be explained by their rapid variability or washing out against a high level of nonthermal power-law continuum (which is not excluded by spectral fitting).

Thermal X-ray spectra of a metal-rich shell ejected by an SN preceding GRB for a few days would rather show photo-recombination edges and not stationary emission lines with time evolution due to geometrical factor.

In our model, it appears more natural to consider that no blue-shifted X-ray lines were observed, if the clumpy medium is a circumstellar envelope produced by slow superwind from the GRB progenitor. The case is even stronger if what we observe is a nearby clumpy cloud in a star-forming region. If the significant blue-shift of the X-ray lines will be confirmed, it will provide a strong evidence that the GRB is preceded by a supernova. However, if these rapidly moving clouds are hydrogen rich, they can hardly be located at such small distances as inferred by Reeves et al. (2002a) and the preceding supernova must occur several months or even years before the GRB event (the supranova scenario, Vietri and Stella 1998).

Apparently, the adequate explanation of the observed spectrum of X-ray afterglow of GRB

011211 should be sought for within the frames of a combined model of photoionization heating of an inhomogeneous medium around the GRB progenitor and time-dependent collisional ionization in more dense condensations with an optical thickness for scattering about 1. Clearly, the calculation of realistic X-ray spectra from such media require appropriate account for radiative transfer effects, which are beyond the scope of the present work.

5 Conclusion

We have calculated thermal X-ray emission spectra of optically thin thermal plasma using a time-dependent treatment of collisional ionization. We show that an instant heating of this plasma up to the 10-keV temperatures produces time-dependent X-ray emission spectra in which lines of α-element metal ions and iron at different ionization states are apparent. We propose a model of thermal X-ray emission for the observed early X-ray afterglow of GRB 011211, in which a narrow gamma-ray beam passes through clumpy interstellar medium, not obligatorily genetically related to GRB. The non-stationarity of the X-ray spectrum is related not to a geometrical factor (time retardation from different parts of the shell), but to a physical non-stationarity of the collisional ionization and thermal relaxation of plasma with density of order $10^{11} - 10^{12}$ cm^{-3}. Parameters of such a medium resemble maser condensations in active star-forming regions. We conclude that the account for time-dependent effects in plasma is unavoidable in spectral X-ray diagnostics of the medium around GRB sites within the frame of thermal plasma models.

The work is supported by RFBR grant 02-02-16500. D.I. Kosenko received a partial support through RFBR grants 02-02-27445z and 01-15-99310m. S.I. Blinnikov and E.I. Sorokina are partially supported by RFBR grant 00-02-17230 and thank W. Hillebrandt and other colleagues at MPA (Garching, Germany) for their hospitality and support. They and P. Lundqvist also acknowledge support from Wenner-Gren Science Foundation and Royal Academy of Sweden.

References

[1] Ambwani, K.; Sutherland, P.G.; ApJ, v. 325, p. 820 (1988)

[2] Blandford, R. in Lighthouses of the Universe, Eds. M. Gilfanov, R. Sunyaev, E. Churasov; 381 (2002)

[3] Blinnikov, S.I.; Surveys High Energ. Phys. 15, 37 (2000); (astro-ph/9911138)

[4] Blinnikov, S.I.; Bartunov, O.S.; Astron.Astrophys. 273, 106 (1993)

[5] Blinnikov, S.I.; Kozyreva, A.V.; Panchenko, I.E.; Ast. Rep. 43, 739 (1999)

[6] Blinnikov, S.I.; Postnov, K.A. MNRAS 293, L29 (1998)

[7] Borozdin, K.N.; Trudolyubov, S.P.; (check!!) ApJ subm. (2002) (astro-ph/0205208)

[8] Chevalier, R.A.; Klein, R.I. ApJ 234, 597 (1979)

[9] Chugai, N.N.; Blinnikov, S.I.; Lundqvist, P. et al. Early circumstellar interaction and light curve of supernova 1994W; in press (2002)

[10] Costa, E.; Frontera, F.; Heise, J. et al. Nature 387, 783 (1997)

[11] Falk, E.; Arnett, D.; ApJS 33, 515 (1977)

[12] Frail, D.A.; Kulkarni, S.R.; Sari, R. et al. ApJ 562, L55 (2001)

[13] Kallman, T.R.; McCray, R.; ApJ Supl.Ser., 50, 263 (1982)

[14] Kumar, P.; Narayan, R.; ApJ subm. (2002); (astro-ph/0205488)

[15] Lazzati, D.; Campana, S.; Ghisellini, G. MNRAS 304, L31 (1999)

[16] Lazzati, D. (2002) (astro-ph/0210301)

[17] Mészáros, P.; Rees, M.J.; ApJ 476, 232 (1997)

[18] Mészáros, P.; Ann. Rev. Astron. Astrophys. 40, 137 (2002)

[19] Piran, T.; Phys. Rep. 333, 529 (2000)

[20] Piro, L.; Garmire, G.; Garcia, M. et al. Science 290, 955 (2000)

[21] Pruet, J.; Woosley, S.E.; Hoffman, R.D.; (2002); (astro-ph/0209412)

[22] Rybicki, G.B.; Lightman, A.P.; ©by John Wiley & Sons Inc., "Radiative processes in astrophysics" (1979)

[23] Rutledge, R.E.; Sako, M.; MNRAS in press (2002); (astro-ph/0206073)

[24] Rausher, T.; Heger, A.; Hoffman, R.D.; Woosley, S.E.; ApJ. 576, 323 (2002); (astro-ph/0112478)

[25] Reeves, J.N.; Watson, D.; Osborne, J.P. et al. Nature 416, 512 (2002a)

[26] Reeves, J.N.; Watson, D.; Osborne, J.P. et al.) Astron. Astrophys, in press (2002b) (astro-ph/0206480)

[27] Rees, M.J.; Mészáros, P.; MNRAS 258, P41 (1992)

[28] Rees, M.J.; Mészáros, P.; ApJ 430, L39 (1994)

[29] Spruit, H.; Astron. Astrophys. 341, L1 (1999)

[30] Tatischeff, V.; (2002); (astro-ph/0208397)

[31] Umeda, H.; Nomoto, K.; Tsuru, T.G.; Matsumoto, H.; ApJ. 578 (2002); (astro-ph/0207067)

[32] Usov, V.V.; MNRAS 267, 1035 (1994)

[33] van Paradijs, J.; Kouveliotou, C.; Wijers, R.A.M.J.; Ann. Rev. Astron. Astrophys. 38, 379(2000)

[34] Vietri, M.; Stella, L.; ApJ 507, L43 (1998)

[35] Watson, D.; Reeves, J.N.; Osborne, J. et al.; Astron. Astrophys. 393, L1 (2002)